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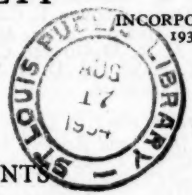

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An Empirical Formula for the Computation of the Indirect Component of Daylight Factor

By R. G. HOPKINSON, Ph.D., M.I.E.E., *(Fellow)*, J. LONGMORE and P. PETHERBRIDGE, B.Sc., *(Member)*.

Summary

An empirical formula for the computation of daylight factor has been developed from formulae proposed by Pleijel, Dresler and Arndt. The formula, like those from which it was derived, assumes that light is inter-reflected in rooms in accordance with the theory of the integrating sphere.

Light entering a room through a window is considered in two parts, (a) that received directly from the sky or by reflection from obstructions above the horizon, and (b) light received by reflection from the ground. In determining the first reflected flux in the room, the sky and obstruction flux referred to under (a) above is modified by the average reflection factor of the floor and certain lower parts of the walls. The ground flux referred to under (b) above is modified by the average reflection factor of the ceiling and by certain upper parts of the walls. These two components of first reflected flux are then added and the theory of the integrating sphere applied.

This formula lends itself easily to simple forms of calculation such as a nomogram or slide-rule type of calculator. It is shown to give results approximating closely to measured values. It is therefore put forward as a tool for use by architects and lighting engineers for the calculation of daylight factor where great precision is not required.

(1) Introduction

The present work was undertaken in response to the need by practising architects for some accurate and simple method of calculating total daylight factor. The most urgent requirement was for a method which would enable the designer to ensure that his completed building would conform to regulations, in some cases statutory, which define the minimum standard of daylighting in certain types of building.

Up to the present these calculations have been made in terms of sky factor which, by definition, does not include the light reflected and inter-reflected by the surfaces of walls, ceiling and floor, etc. Ignorance of the amount of this inter-reflected light has resulted in rooms being designed with excessive fenestration which has contributed to complaints of sky glare.

The need has been shown for a method to be developed which would enable the true daylight factor in the completed building to be calculated with a much greater degree of accuracy than that achieved by the sky factor calculations.

It is assumed that a detailed study has been made by the reader of the various methods now available for the calculation of daylight factor. Most of these methods are referred to by Dresler in his recent paper[1] in such a way that their essential principles can be deduced. It is therefore not necessary to summarise them here.

In addition, the reader should be familiar with the survey given by Petherbridge[2] of methods of sky brightness measurement, and also with the arguments in favour of basing daylight calculations, not on the uniform sky hitherto assumed, but on the Moon and Spencer standard overcast sky; this has the advantage that it is the only stable sky condition that obtains in practice free from complications such as those due to the presence of the sun in a clear blue sky.

The reader should also be familiar with the conceptions (a) "Sky Factor," at present based on a uniform sky, (b) "Direct Component of Daylight Factor," i.e., the light which reaches the working point in the room directly without inter-reflections,

The authors are with the Department of Scientific and Industrial Research at the Building Research Station, Garston, Watford. The manuscript of this paper was first received on September 28, 1953, and in revised form on October 21, 1953.

(c) "Indirect Component of Daylight Factor," i.e., the inter-reflected light, and (d) "Total Daylight Factor" which is the sum of the Direct and Indirect Components.

There are advantages in dealing with the problem of daylight factor calculation in two stages namely (i) the Direct Component based on the established Sky Factor conception and (ii) the Indirect Component considered as an addition to the Direct Component. This approach enables present techniques to be continued rather than supplanted.

Thus the method proposed by Früehling(1), (11) and that developed more recently by Biesele, Arner and Conover(1), (12) both of which are based on the calculation of total daylight factor in one stage only, have not been considered because they require a considerable change in present architectural practice which is not felt to be desirable. For the same reason the method described by Hopkinson and Longmore(3) has not been considered in developing the present formula although the extensive measurements on which the method is based have been employed freely in the present development.

Of the methods available which deal with the problem in two stages, it has been decided as a result of experience in their use by the Building Research Station that the formulae proposed by Arndt and by Dresler go nearest to achieve the compromise required by architects between accuracy on the one hand and simplicity and expediency on the other hand.

(2) Development of the Integration Formulae for the Computation of the Indirect Component of Daylight Factor

The integration formulae for the computation of inter-reflected light in rooms are based on the theory of inter-reflection developed by Ulbricht for the integrating sphere. They therefore differ from the methods developed by Moon and Spencer from the theory of the inter-reflection of light in cylinders proposed by Buckley. The error involved in applying all formulae of this type to a room of shape well removed from the ideal sphere or cylinder is likely to be considerable, but can be made negligible for practical purposes. Any such empirical formula must not, however, be used when the conditions are extreme.

Reference should be made to the paper by Dresler(1) for the development of the integration formulae. The essential difference between Dresler's approach and that of Arndt is that Dresler considers it necessary to calculate the primary flux distribution over the interior surfaces in the room, whereas Arndt overcomes the necessity for calculating the primary flux distribution by treating all flux entering the room through the window as of equal weight, whether it comes from the sky, from the ground or from some obstruction.

The basic formula behind both methods is:—

$$\text{Average inter-reflected component of the illumination within the interior} = \frac{\text{First reflected flux from interior surfaces}}{A\,(1 - R)} \quad \ldots(1)$$

where A is the area of all the surfaces in the room (ceiling, walls, floor and windows)

and R is the average reflection factor of all the surfaces in the room (ceiling, walls, floor and windows) expressed as a decimal part of unity.

In Dresler's method the numerator of this equation is determined in terms of the mean first incident illumination on each of the various interior surfaces, weighted first by the area of the surfaces to give incident flux and then by the reflection factor of the surfaces to give reflected flux. The mean first incident illumination on the interior surfaces can be derived by the method given by Dresler (from Higbie's

formula), but it is preferable to express it in terms of the mean sky factor appropriate to each interior surface.

The procedure is therefore, first, to calculate for each of the relevant surfaces in the room the mean sky factor for that surface; second, to calculate the total flux incident on the surface, and third to calculate the reflected flux from the surface. The sum of all these first reflected fluxes gives the total amount of first reflected flux in the room.

The number of calculations of sky factor which is necessary depends on the number of components into which the room is broken down. The greater the accuracy demanded, the greater is the number of components into which the room must be divided and therefore the greater is the labour involved in the calculation of the first reflected flux.

The calculation of all these sky factors (or the equivalent calculations by the Dresler-Higbie method) in a complicated building site with numerous obstructions would represent a considerable amount of labour. It is this which makes Dresler's method too complicated for use as a day-to-day tool by the practising architect, however valuable it may be for the lighting specialist concerned either with the design or the legal aspect of natural lighting.

In Arndt's method the first reflected flux from the interior surfaces is obtained by weighting the product of the window area and the incident illumination normal to the window plane by the mean reflection factor of the interior surfaces. Therefore, only one sky factor determination is required and the labour inherent in the Dresler formula is avoided.

Unfortunately Arndt's simplification is only achieved at the sacrifice of accuracy. This was shown by an extensive series of calculations made to compare the inter-reflected components as obtained by Dresler's formula and by Arndt's formula, with the amount of reflected light actually measured by two of the present authors using models[3]. These comparisons showed that Arndt's formula (as given in Dresler's paper) always seriously over-estimated the amount of inter-reflected light. It was felt that, as a result of these comparisons, the simplicity introduced by Arndt's formula as compared to that of Dresler is achieved at too great a sacrifice of accuracy.

An inspection of the principles behind the Arndt formula reveals why this consistent over-estimate of inter-reflected component occurs. Arndt gives equal weight to all the flux entering through the window in that, in order to obtain the first reflected flux, he modifies the incident flux by the average reflection factor of all the surfaces in the room. In practice, however, the ceiling is usually of high reflection factor and the floor of low reflection factor. The ceiling never receives any direct light from the sky and the floor never receives any direct light from the ground. Consequently, in the Arndt formula the sky flux (or that received from sky and obstructions above the horizon) is modified by a figure for the reflection factor which is in excess of the reflection factor of the surfaces which actually receive the sky flux. The sky flux will usually constitute the greater part of the entering flux, and so the first reflected flux will be over-estimated.

It would therefore appear logical to treat the flux entering the room in two parts: (a) That entering the room directly from the sky or from those obstructions which are above the horizon, and (b) that flux which enters the room directly from the ground (that is, skylight reflected from the ground). Component (a) should then be modified by the average reflection factor of the surfaces as seen from the sky and component (b) should be modified by the average reflection factors of the surfaces as seen from the ground.

(3) Derivation of the Proposed Formula

Arndt's formula (as given in Dresler's paper) for the indirect component of daylight factor can be written as:—

$$\text{Indirect component (per cent.)} = \frac{W}{A} \times \frac{R}{1-R} \times S \quad \ldots\ldots(2)$$

where W = window area

S = "sky factor" equivalent of illumination normal to centre of window (per cent.), i.e. $S = \dfrac{\text{illumination normal to window}}{\text{total outdoor illumination}}$

and A and R have the same definitions as for equation (1).

At the 1953 meeting of the C.I.E. Daylighting Committee, Arndt[4] proposed a simplification of the formula given above, based on the following assumptions:—

(a) The ground and obstructing buildings both have a brightness 1/10th that of the sky.

(b) The outlines of obstructing buildings are horizontal and parallel to the window wall.

Arndt's simplified formula is:—

$$\text{Indirect component (per cent.)} = \frac{W}{A} \times \frac{R}{1-R} \times K \quad \ldots\ldots(3)$$

where K is a function of the angle of the obstruction from the centre of the window (see Table 1).

Table 1

Variation of the Function (K) in Arndt's Simplified Formula with Angle of Obstruction

Angle of obstruction from centre of window (degrees above horizontal)	K (unglazed window and uniform sky)	K (glazed window and Moon and Spencer non-uniform sky)
0 (no obstruction)	55	37
10	47	34
20	40	30
30	32	26
40	26	21
50	20	16
60	16	12
70	13	10
80	11	9

The advantage of the simplified formula is that it can be used without the need to determine any sky factors.

The values of K given by Arndt are related to unglazed windows and to a sky of uniform brightness. It is usual, however, to consider the windows as being glazed. Furthermore, as mentioned earlier, it is increasingly recognised that the Moon and Spencer brightness distribution is more representative of actual overcast skies than is a uniform distribution.

The values of K for various angles of obstruction in Table 1 have therefore been given both for unglazed windows and a uniform sky and for glazed windows and a Moon and Spencer sky.

As has been explained earlier, the proposed formula is derived from Arndt's formula by treating the flux entering the room in two parts. This has been effected by replacing

the term $(K \times R)$ in the numerator of equation (3) by the expression $(C_1R_1+C_2R_2)$, where C_1 and C_2 are functions of the flux entering the room from above and below the horizontal respectively, and R_1 and R_2 are functions of the average reflection factors of the lower and upper surfaces of the room respectively.

In practice, C_1 is the "sky factor" equivalent of the light flux received normally at the inside of the window from above the horizontal. It comprises two components, one due to light from the visible sky and the other due to light reflected from the obstructions, if any.

Values of the former component have been calculated for varying angles of obstruction, using a specially drawn Waldram diagram based on a Moon and Spencer sky and a glazed window. Values of the latter component have been calculated for varying angles of obstruction, using a Waldram diagram based on a uniform light source and a glazed window(5). These values were corrected to allow for the fact that the brightness of the obstruction was assumed to be 1/10th of the mean sky brightness.

In practice, C_2 is the "sky factor" equivalent of the light flux received normally at the inside of the window from below the horizontal. This flux is assumed to be received by reflection from ground having a brightness 1/10th of the mean sky brightness.

The value of C_2 is constant and is independent of the angle of obstruction.

Consideration has been given to the method of calculating the average reflection factor of the lower surfaces of the room which modify the sky light (R_1) and of the upper surfaces of the room which modify the ground light (R_2).

In determining these average reflection factors it should be remembered that light from the sky reaches the walls with a different distribution of angular incidence from that with which it reaches the floor. A similar consideration applies to the ground light and its incidence on the ceiling and walls.

The original proposal was to compute the average reflection factors in terms of the "sky factors" of the room surfaces as seen at an agreed point on the window. This proposal has, however, been rejected for the moment in favour of the more simple procedure of dividing the room surfaces into two parts by a plane through the mid-height of the window.

To obtain the first reflected flux from the sky, the sky flux received through the window (C_1) is modified by the average reflection factor of the floor and the lower walls up to this plane. To obtain the first reflected flux from the ground, the ground flux received through the window (C_2) is similarly modified by the average reflection factor of the ceiling and the upper walls down to this plane.

When calculating these average reflection factors, the reflection factor of the window wall should be excluded since this wall receives no light directly through the window but only after reflections in the interior.

The proposed formula therefore becomes:—

$$\text{Indirect component (per cent.)} = \frac{W}{A(1-R)} \times [C_1R_{fw}+C_2R_{cw}] \quad \ldots\ldots\ldots\ldots\ldots\ldots (4)$$

where R_{fw} = the average reflection factor of the floor and those parts of the wall below the plane of the mid-height of the window (excluding the window wall)

and R_{cw} = the average reflection factor of the ceiling and those parts of the wall above the plane of the mid-height of the window (excluding the window wall).

If the diffuse transmission factor of window glass to a uniform source of light of infinite extent is assumed to be 85 per cent(6) then it can be shown that the constant value of C_2 is 4.25 $(=50 \times 0.1 \times 0.85)$.

The formula is easier to use, however, if the value of C_2 is adjusted to 5.0. This

Table 2

Variation of the Function (C) in the Proposed Integration Formula with Angle of Obstruction

Angle of obstruction from centre of window (degrees above horizontal)	C
0 (no obstruction)	39
10	35
20	31
30	25
40	20
50	14
60	10
70	7
80	5

can be done provided the values of C_1 are correspondingly adjusted. The final form of the formula is therefore:—

$$\text{Indirect component (per cent.)} = \frac{0.85W}{A(1-R)}[CR_{fw} + 5R_{cw}] \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (5)$$

where values of C are given in Table 2.

The values of C given in this table are dependent on the following assumptions:—

(a) The sky brightness distribution is that of the "Moon and Spencer" sky;

(b) The ground and any obstructions have a brightness one-tenth that of the mean sky brightness;

(c) The obstructions are of infinite extent and have their outlines horizontal and parallel to the plane of the window wall. (If the obstructions do not fulfil these conditions, an estimate should be made of the equivalent horizontal obstruction.)

(d) The diffuse transmission factor of the window glass to a uniform source of light of infinite extent is 85 per cent.;

(e) The losses arising from the transmission through the window glass of the light from the non-uniform sky, the ground and any obstruction are properly allowed for.

The accuracy of the proposed formula has been examined for the conditions of a side-lighted school classroom studied in model form. Fig. 1 shows, for example, the relation between ceiling height and the indirect components of daylight factor as determined by:—

(i) Dresler's formula;

(ii) Arndt's simplified formula in its original form—equation (3) and the values of Table 1, middle column;

(iii) Arndt's simplified formula but modified for the "Moon and Spencer" sky brightness distribution and for glazed windows—equation (3) and the values of Table 1, right-hand column;

(iv) The proposed formula—equation (5) and the values of Table 2;

(v) Measurements in the model classroom[3].

It will be seen that the proposed formula and Dresler's formula both give results which agree with the measured values. Similar results are available covering a wide range of conditions.

It has been concluded as a result of these calculations that the proposed formula

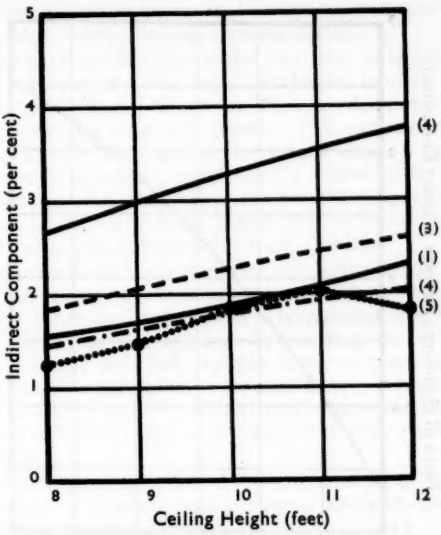

Fig. 1. Relationship between ceiling height and values of indirect component of daylight factor as determined by :—

(1) Dresler's formula. ——— (lower line).

(2) Arndt's simplified formula in its original form—equation (3) and the values of Table 1, middle column. ——— (upper line).

(3) Arndt's simplified formula but modified for the Moon and Spencer sky brightness distribution and for glazed windows—equation (3) and the values of Table 1, right-hand column.

(4) The proposed formula—equation (5) and the values of Table 2, — - — - —

(5) Hopkinson and Longmore's measurements in a model room. ••●•••●••

is of sufficient accuracy for the work of the practising architect. It gives results which are in close agreement with the more complicated procedure necessary if Dresler's formula is employed, and with model measurements.

The proposed formula has, however, certain limitations which are inherent in all formulae based on the assumption that a room will behave in the same way as an integrating sphere as regards the inter-reflection of light. These limitations, however, are not of serious consequence provided the formula is not used under conditions where there is a very great diversity in the reflection factor of the various surfaces.

Another more serious limitation is that it is not possible to predict the variation of the inter-reflected light with the position in the room. The formula will give only a figure for the average reflected component for any part of the room.

The reflected component is not, however, independent of position in the room and this is therefore a limitation which cannot be neglected. It is of particular importance if the formula is to be used for the calculation of daylight factor for compliance with statutory regulations which are often drafted in terms of *minimum* daylight factor rather than in terms of *average* daylight factor in the room.

No simple method of relating the average daylight factor in the room to the distribution of daylight factor has been devised. The following approach is empirical and is based on the consideration of model studies in side-lighted rooms and on other model studies in a different shape of room.

Fig. 2 relates the ratio of the minimum to the average indirect component of daylight factor and the average reflection factor of the interior of the model room. This relation is not, however, the same for all room configurations. It varies for the given model room with variation in ceiling height, and it differs for a room which is lighted by a window down the long wall from one which is lighted by a window on the short wall.

From a consideration of all these factors Table 3 has been derived as a practical method of relating the minimum indirect component of daylight factor in a side-lighted room with the average indirect component. This table applies only to side-lighted

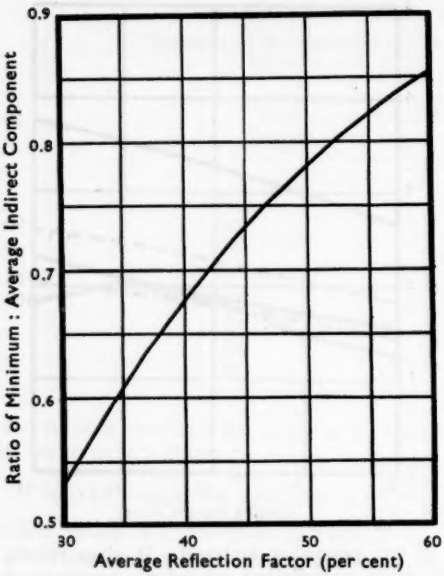

Fig. 2. Variation of the ratio minimum: average indirect component with average reflection factor of room interior. (Applicable to rooms having ceilings of approx. 70 per cent. r.f. and floors of approx. 15 per cent. r.f.).

rooms and only to rooms lighted from one side. The minimum daylight factor will occur near the wall farthest from the window.

In rooms lighted from more than one side, or lighted from roof lighting, no ready means is available of relating the average indirect component of the daylight factor to the minimum, but various expedients will occur to the practitioner as experience with the method is gained. One method of dealing with the two-side lighted problem is illustrated by the worked example in Appendix 1.

The proposed formula lends itself to the construction of a nomogram or calculator. This development is considered to be essential if the formula is to be used by practising architects, and two nomograms are given in Appendix 3.

(4) Conclusions

An empirical formula has been developed for the computation of the indirect component of daylight factor. The indirect component of daylight factor added to the direct component of daylight factor will yield the total daylight factor. It is the total daylight factor which is of importance in determining the natural lighting in relation to the design of a room.

Two stages are necessary in the computation of total daylight factor, (a) the direct

Table 3

Relationship between Ratio of Minimum : Average Indirect Component and Type of Decoration for Side-lighted Rooms

Type of decoration	Ratio : $\frac{\text{Minimum}}{\text{Average}}$
Dark walls (reflection factor less than 10 per cent.)	0.55
Average walls (reflection factor approximately 35 per cent.)	0.7
Light walls (reflection factor greater than 70 per cent.)	0.85

component must be determined by some established technique and (b) the indirect component must be calculated and the two added to give the total daylight factor.

It has been decided after much consideration that this is the best way in which daylight calculations can be put forward at this stage. Although considerable time was needed to establish the use of the Graded Sky(7) Factor tables, the Waldram diagram(8) and the B.R.S. protractors(9), these techniques are now well known. It is considered unwise to destroy the confidence that has already been built up in these techniques by any proposal which would result in their being completely supplanted by a new method which has to be learned from the beginning. For this reason the present proposals have been based on the developments of Dresler and Arndt rather than on those of Früehling and others which demand an entirely new approach to the problem.

With the present method the architect can make his preliminary sky factor calculations from his rough sketch plans and can modify his fenestration at this early stage in a way with which he is now familiar. When he has achieved a fenestration which satisfies him on all grounds—not only that of natural lighting—he can then make a more detailed calculation to determine whether his total daylight factor is going to meet the relevant demands, such as statutory regulations. He can then make any modifications which may be required. In such a way, he can arrive at a figure for the daylight factor which will agree within a sufficient order of accuracy with that which will be measured in the completed building.

This paper is based on the work carried out as part of the programme of the Building Research Board of the Department of Scientific and Industrial Research and is published by permission of the Director of Building Research.

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Appendix I

Application of the Proposed Formula to the Daylighting of a Classroom

The following worked example demonstrates an application of the proposed formula to a classroom lit by a main window and a clerestory as illustrated in Fig. 3.

It is required to find whether the daylighting in the classroom conforms with the present (1954) statutory regulations, i.e., to find whether the daylight factor (total) at any part of the useful area of the working plane falls below 2 per cent.

As can be seen from the figure, the main window faces an obstructing building 50 ft. distance from it whose outline has an altitude of 10 deg. at the centre of the window. Similarly the clerestory faces an obstruction 20 ft. distance from it of altitude 20 deg.

The windows are glazed and the sky conforms with the Moon and Spencer brightness distribution.

The reflection factors of the interior surfaces are :—

Walls	= 0.30
Ceiling	= 0.70
Floor	= 0.20
Window glass	= 0.15 (assumed value for diffuse light)

The reflection factors of the ground and obstructing buildings are assumed to be such that their brightnesses are 1/10th of the mean sky brightness.

The proposed formula is first used to calculate the indirect components of daylight factor due to the two windows. The steps in the application of the formula are as follows :—

(i) Total surface area of interior = $A = 2x\,(10 \times 40 + 10 \times 24 + 24 \times 40)$
$= 3{,}200$ sq. ft.

(ii) Average reflection factor of interior = $R =$

$$\frac{\text{Wall area} \times 0.30 + \text{Ceiling area} \times 0.70 + \text{Floor area} \times 0.20 + \text{Glass area} \times 0.15}{\text{Total surface area}}$$

$$= \frac{1040 \times 0.30 + 960 \times 0.70 + 960 \times 0.20 + 240 \times 0.15}{3200}$$

$$= \frac{1212}{3200} = 0.38$$

Hence $1 - R = 0.62$

(iii) Main window : Mid-height of window is 6 ft. 6 in. from floor. Average reflection factor of room below 6 ft. 6 in. level, excluding wall containing main window = R_{fw}

$$= \frac{\text{Wall area} \times 0.30 + \text{Floor area} \times 0.20}{\text{(Wall + Floor) area}}$$

$$= \frac{676 \times 0.30 + 960 \times 0.20}{1636}$$

$$= \frac{395}{1636} = 0.24$$

Average reflection factor of room above 6 ft. 6 in. level, excluding wall containing main window = R_{cw}

$$= \frac{\text{Wall area} \times 0.30 + \text{Ceiling area} \times 0.70 + \text{Glass area} \times 0.15}{\text{(Wall + Ceiling + Glass) area}}$$

$$= \frac{292 \times 0.30 + 960 \times 0.70 + 72 \times 0.15}{1324}$$

$$= \frac{770}{1324} = 0.58$$

Value of C for a 10-deg. obstruction is 35 (see Table 2).

The average indirect component of daylight factor in the classroom due to the main window is given by :—

$$\frac{0.85\ W}{A(1-R)} \times (CR_{fw} + 5R_{cw})$$

Substituting numerical values :—

$$\text{Indirect component (per cent.)} = \frac{0.85 \times 168}{3200 \times 0.62} \times [35 \times 0.24 + 5 \times 0.58]$$

$$= \frac{0.85 \times 168 \times 11.3}{3200 \times 0.62}$$

$$= \underline{0.81} \text{ per cent.}$$

(iv) Clerestory: Mid-height of window is 8 ft. 6 in. from floor. Average reflection factor of room below 8 ft. 6 in. level, excluding wall containing clerestory = R_{fw}

$$= \frac{\text{Wall area} \times 0.30 + \text{Floor area} \times 0.20 + \text{Glass area} \times 0.15}{(\text{Wall} + \text{Floor} + \text{Glass}) \text{ area}}$$

$$= \frac{752 \times 0.30 + 960 \times 0.20 + 132 \times 0.15}{1844}$$

$$= \frac{437}{1844} = 0.24$$

Average reflection factor of room above 8 ft. 6 in. level, excluding wall containing clerestory = R_{cw}

$$= \frac{\text{Wall area} \times 0.30 + \text{Ceiling area} \times 0.70 + \text{Glass area} \times 0.15}{(\text{Wall} + \text{Ceiling} + \text{Glass}) \text{ area}}$$

$$= \frac{120 \times 0.30 + 960 \times 0.70 + 36 \times 0.15}{1116}$$

$$= \frac{713}{1116} = 0.64$$

Value of C for a 20-deg. obstruction is 31 (see Table 2).

The average indirect component of daylight factor in the classroom due to the clerestory is given by:—

$$\frac{0.85 \times 72}{3200 \times 0.62} \times [31 \times 0.24 + 5 \times 0.64]$$

$$= \frac{0.85 \times 72 \times 10.6}{3200 \times 0.62}$$

$$= 0.33 \text{ per cent.}$$

The *average* indirect component in the classroom due to both windows is therefore 0.81 + 0.33 = 1.14 per cent. This is likely to occur at points midway between the two window walls.

At points near the clerestory wall the indirect component due to the main window will be a minimum. To obtain this minimum value, the average indirect component determined above has to be multiplied by the ratio of minimum : average indirect component appropriate to the average reflection factor of the room interior. This can be done by using either an approximate value of the ratio from Table 3 or a more precise value from Fig. 2.

For the purposes of this example, a value from Fig. 2 has been used. For a room of average reflection factor 38 per cent., the ratio is 0.65

The actual indirect component near the clerestory wall due to light from the main window will therefore be of the order of $0.81 \times 0.65 = 0.53$ per cent. The indirect component near the clerestory wall due to light from the clerestory will, however, be greater than the average value of 0.33 per cent. determined above. The actual indirect component near the clerestory wall due to light from both windows will therefore be greater than $0.53 + 0.33 = 0.86$ per cent.

Similarly the actual indirect component near the main window wall due to light from both windows will be greater than $0.81 + 0.33 \times 0.65 = 0.81 + 0.21 = 1.02$ per cent.

The indirect component of daylight factor in the room is therefore determined as:—

Near the main window—greater than 1.02 per cent.
Near the clerestory—greater than 0.86 per cent.
In the middle of the room—about 1.14 per cent.

If the daylighting in the classroom is required to meet a statutory minimum of

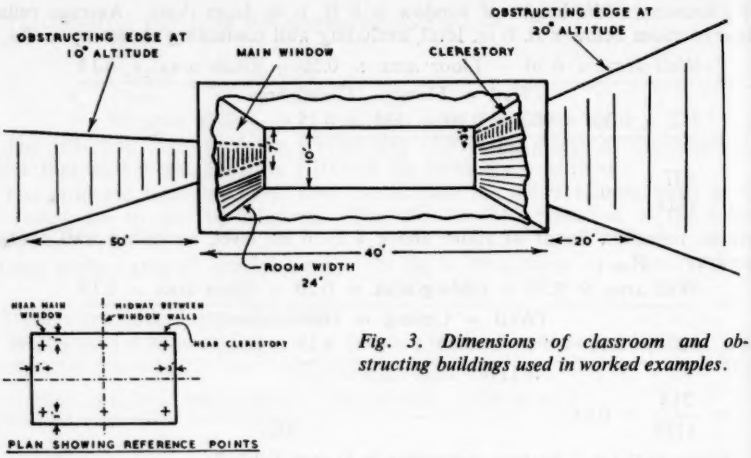


Fig. 3. Dimensions of classroom and obstructing buildings used in worked examples.

2 per cent. daylight factor (total), it therefore follows that the direct component must have the following values:—

Near the main window 2.0 − 1.02 = 0.98 per cent. or somewhat less
Near the clerestory 2.0 − 0.86 = 1.14 per cent. or somewhat less
In the middle of the room 2.0 − 1.14 = 0.86 per cent. but not less

The direct component is in effect the sky factor (but with certain provisos with respect to glazing losses and to the sky brightness distribution—see later).

The sky factor can be determined from the plan and elevation of the classroom and of its obstructing buildings using any well-established technique such the N.P.L. Graded Sky Factor Tables (7), the Waldram diagrams (5, 8) or the B.R.S. protractors (9), With all of these techniques provision is made for glazing loss corrections.

The sky factors relevant to the worked example were calculated for a working plane height of 2 ft. 6 in., using the protractors for vertical glazing. As is normally the case, only the sky visible through the windows was considered.

Reference points were taken on a line parallel to one of the side walls and 3 ft. distance from it (Fig. 3). This line was chosen as being at the boundary of the useful working area where the direct components would be a minimum.

The sky factors so obtained are shown in Table 4 together with the indirect components calculated above. These values show that near the window walls the sky factors plus indirect components are well above the statutory minimum of 2 per cent. daylight factor. Midway between the window walls the sky factor is only 1.39 per

Table 4

Calculated Values of Sky Factor and Indirect Component at Three Positions in Classroom

Position	Sky Factor (S)	Indirect Component (I)	S + I
Near main window*	21.6	>1.02	>22.6
Near clerestory*	5.35	> 0.86	> 6.21
Midway between window walls	1.39	c 1.14	c 2.53

* Reference points located at 3ft. from respective window walls.

Table 5

Conversion of Sky Factors into Direct Components of Daylight Factor

Contribution	Sky factor midway between window walls (S.F.)	Mean altitude of visible sky (degrees)	Value of conversion factor (Z)	Direct component (=S.F. x Z)
Due to main window	1.15	15	0.65	0.75
Due to clerestory	0.24	20	0.72	0.17

cent., but the total daylight factor is more than 2 per cent. It is, however, rather close to the minimum and it would be well to give it further examination.

Strictly, in order to obtain true values of the direct component, the values of sky factor should be modified to the Moon and Spencer sky brightness distribution, since the sky factor as defined is based on a sky of uniform brightness. The direct components under an overcast (Moon and Spencer) sky can be obtained by multiplying the sky factors by the relevant figures given in Table 6 (Appendix II).

The total daylight factors near the windows are clearly well above the statutory minimum of 2 per cent. and no useful purpose would be served in analysing this part of the problem further.

A more accurate analysis is, however, desirable for the total daylight factor midway between the window walls, where the statutory minimum of 2 per cent. is approached. The relevant values of sky factor have therefore been modified as shown in Table 5. This table gives the mean altitudes of the visible sky, the appropriate values of the modifying factor Z from Appendix 2 necessary to convert the sky factors into direct components and finally the Direct Components of Daylight Factor.

The total daylight factor at the two points midway between the window walls and 3 ft. in from either side wall is therefore the sum of:—

Direct component from main window = 0.75 per cent.
" " " clerestory = 0.17 per cent.
Indirect component from main window = 0.81 per cent.
" " " clerestory = 0.33 per cent.
Total = 2.06 per cent.

The daylight factor at these two points is therefore seen to be slightly greater than the statutory minimum of 2 per cent. The daylighting of the classroom can therefore be said to conform to the statutory regulations.

A comparison of the final value (2.06 per cent.) with that given in Table 4 (2.53 per cent.) demonstrates the significant effect which an allowance for a non-uniform sky can have on the calculated value of total daylight factor.

The above example shows the steps necessary to estimate total daylight factor in relation to a statutory minimum level. Equally, however, the method can be applied to a comprehensive study of the daylight in a room. Values of sky factor (modified for the Moon and Spencer sky) can be obtained for different points in a room and the indirect component added, so that contours of equal total daylight factor can be obtained.

Appendix 2

Conversion from Sky Factor to Direct Component of Daylight Factor

Sky Factor as defined is a geometrical property of the room and is based on the area of visible sky in relation to the reference point, the sky being assumed to be of a uniform

Table 6

Values of Conversion Factor (Z) corresponding to Mean Altitude of Visible Sky

Mean of altitudes of upper and lower sight lines to window (degrees)	Conversion factor (Z)
5	0.50
10	0.58
20	0.72
30	0.86
40	0.98
42	1.00
45	1.04
50	1.09
60	1.17
70	1.24
80	1.27
85	1.28

brightness. It can be calculated precisely by formulae or with the aid of such devices as the B.R.S. Protractors or the Waldram diagram.

The Direct Component of Daylight Factor is a measure of the light actually received at the reference point and takes into account glazing losses and any non-uniformity in sky brightness.

In order to calculate direct components of daylight factor it is therefore necessary to apply corrections for glazing losses and sky brightness distribution to the calculated values of sky factor.

It is already customary to incorporate an allowance for glazing losses when calculating sky factors. The incorporation of a further allowance for sky brightness distribution can be simply effected by multiplying the sky factor (based on a uniform sky) by one of the conversion factors (Z) in Table 6([10]), depending on the mean altitude of the sky visible from the reference point. These conversion factors are based on a sky having a Moon and Spencer sky brightness distribution. The resultant value after incorporation of the two allowances gives the direct component of daylight factor for a Moon and Spencer overcast sky. Such direct components are less than the sky factors for low side windows and greater than the sky factors for top lighting.

Summarising :—

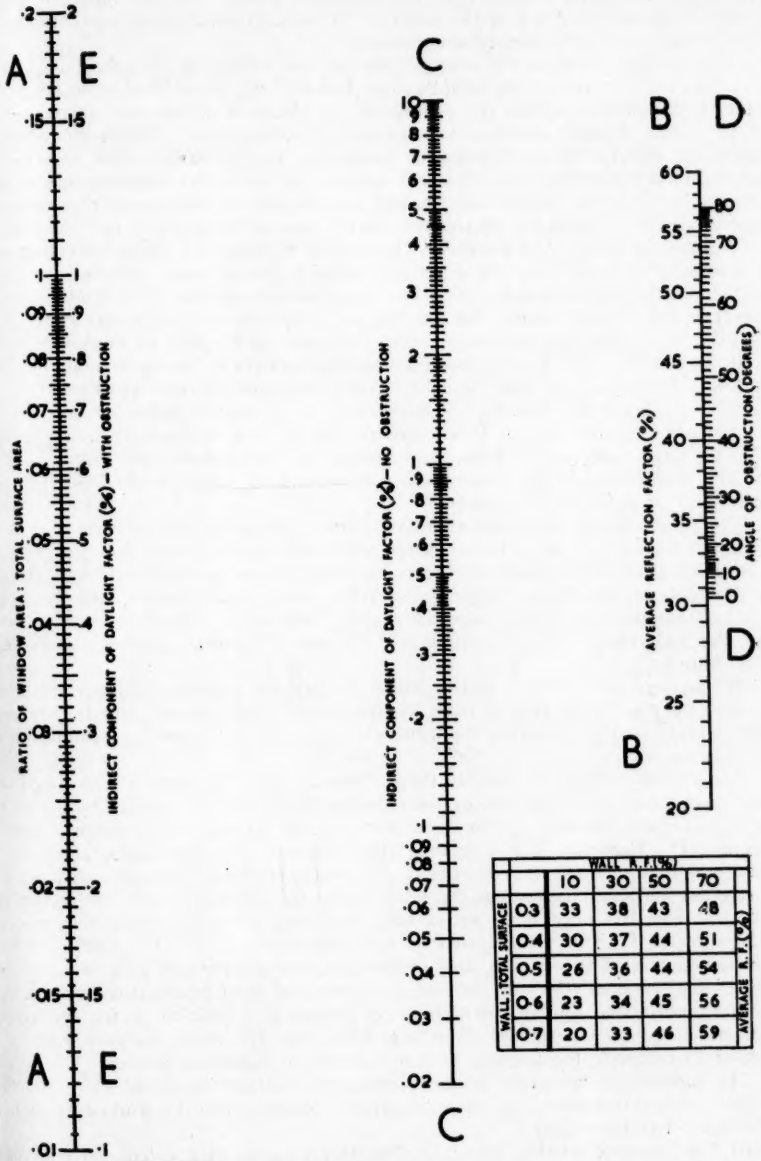
Sky Factor (uniform sky corrected for glazing losses) x Z =
Direct Component of Daylight Factor (Moon and Spencer sky), where Z has the values given in Table 6.

Appendix 3

Development of a Nomogram for the Rapid Determination of the Indirect Component of Daylight Factor

The proposed formula lends itself readily to presentation in the form of a nomogram or slide-rule calculator, and such development is considered essential if the formula is to be used by practising architects.

Several nomograms have been constructed. Nomogram I shown in Fig. 4 is designed to give results which agree with the proposed formula under certain limiting conditions. This expedient enables the calculation of the indirect component of the daylight factor to be undertaken on a simple nomogram. In addition to the assumptions given in the main paper for the development of the proposed formula it is



WALL : TOTAL SURFACE	WALL R.F.(%) 10	30	50	70	AVERAGE R.F.(%)
0·3	33	38	43	48	
0·4	30	37	44	51	
0·5	26	36	44	54	
0·6	23	34	45	56	
0·7	20	33	46	59	

Fig. 4. Nomogram I; Average indirect component of daylight factor.

necessary in the construction of the nomogram to assume that the reflection factors of the ceiling and floor are of the order of 70 per cent. and 15 per cent. respectively (with a small variation permissible either way).

This nomogram gives the *average* indirect component of daylight factor in the room. In order to obtain the *total* daylight factor at any point it is necessary to add, to the value determined from the nomogram, the direct component at the point —

i.e., Total daylight factor = Average indirect component + Direct component.

[Note : The direct component value for insertion in the above expression must be that as determined, not for the uniform sky as assumed in the present definition of sky factor but modified for the Moon and Spencer sky brightness distribution. Appendix 2 demonstrates how this direct component can be obtained from the value of sky factor.]

Nomogram II (Fig. 5) is essentially the same as Nomogram I above but incorporates an automatic correction for the difference between the *minimum* indirect component and the *average* indirect component. The correction was derived from model measurements (see Fig. 2) and assumes the distribution of the indirect component to be similar in most types of side-lighted room. This nomogram applies only to single-side lighted rooms (where the minimum indirect component occurs at points remote from the window). The *minimum* total daylight factor is therefore obtained as follows :—

> Total Daylight Factor (minimum) = Minimum Indirect Component + Minimum Direct Component at back of room (i.e., sky factor modified for Moon and Spencer sky brightness distribution).

This nomogram should be used when calculating the minimum daylight factor for the purpose of statutory regulations.

For rooms lighted from more than one side a certain amount of care is required. When there are windows in two opposite walls the indirect component will be more uniformly distributed throughout the room than with single-side lighting. If there are obstructions of different angles of altitude outside each window, the calculation must be made for each window separately, using Nomogram I (Average value). Otherwise the calculation can be made for the two windows together, again using Nomogram I.

When there are windows on two adjacent sides, the minimum indirect component will occur in the corner remote from the windows. Hence Nomogram II (Minimum value) should be used, treating the windows separately or together depending on the obstructions.

The average reflection factor of the surfaces in the room must be calculated on a direct proportion basis—multiplying the reflection factor of each surface by the area of that surface and dividing by the total surface area to find the average value (see Appendix 1). However, if it is assumed that the wall reflection factor alone can be varied and that the reflection factors of the ceiling and floor remain constant, then the average reflection factor can be related to wall reflection factor and room proportions. This has been done and a table has been prepared which is reproduced on Nomogram I. The values given in this table apply strictly to ceiling and floor reflection factors of 70 per cent. and 15 per cent. respectively and to a (window/total surface area) ratio of 0.05 but they can be applied to most practical conditions.

For rapid estimations of the indirect component it is sufficient to use the average reflection factor as determined from this table, but for more accurate work it is essential to calculate the average reflection factor as described above.

The method of operation of the Nomograms is best illustrated by a practical example. For this purpose the school classroom considered in the worked example of Appendix 1 has been used.

(i) The ratios of window area: total surface area are first calculated and found to be:—

$$\text{Main window} = \frac{168}{3200} = 0.0525 : \text{Clerestory} = \frac{72}{3200} = 0.0225$$

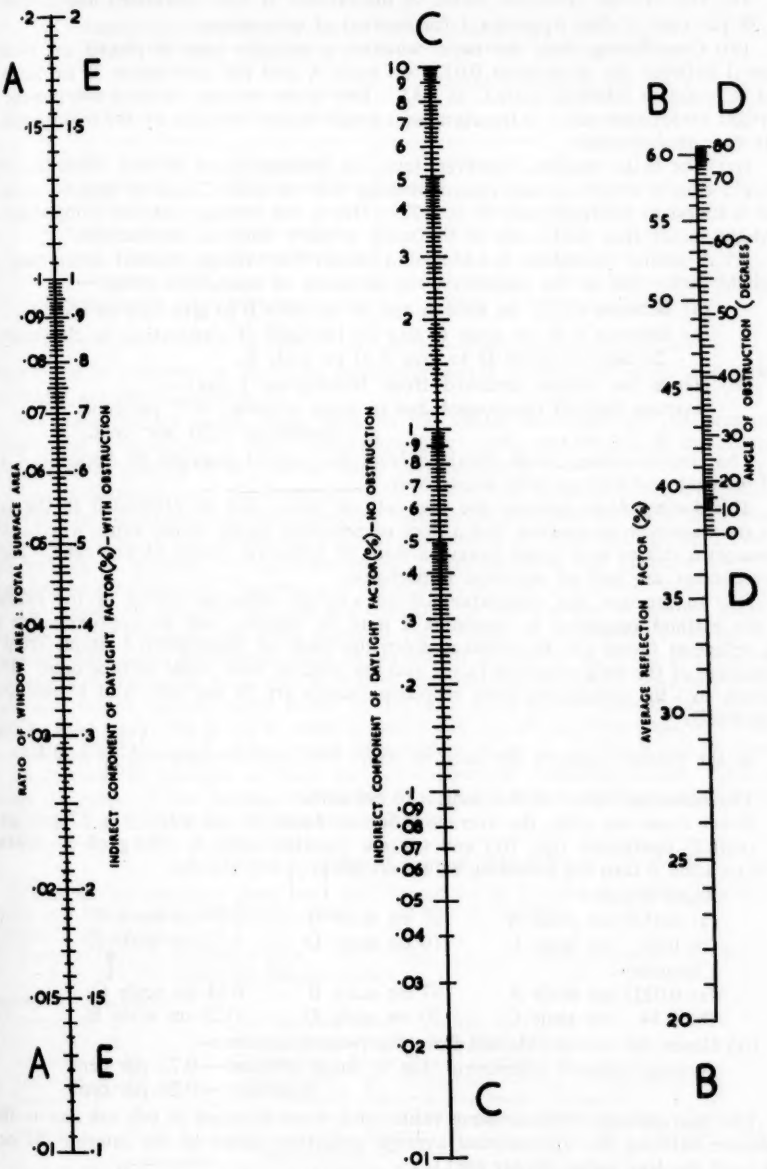


Fig. 5. Nomogram II; Minimum indirect component of daylight factor.

(ii) The average reflection factor of the interior is then calculated and found to be 38 per cent. (See Appendix 1 for method of calculation.)

(iii) Considering, first, the main window, a straight edge is placed on Nomogram I between the graduation 0.0525 on scale A and the graduation 38 on scale B and is found to intercept scale C at 0.83. This is the average indirect component of daylight factor (per cent.) in the classroom which would be given by the main window if it were unobstructed.

(iv) The main window, however, faces an obstruction of 10 deg. altitude. The straight edge is therefore then placed between 0.83 on scale C and 10 deg. on scale D and is found to intercept scale E at 0.77. This is the average indirect component of daylight factor (per cent.) due to the main window with its obstruction.

(v) A similar procedure is adopted to obtain the average indirect component of daylight factor due to the clerestory, the sequence of operations being:—

(a) Between 0.0225 on scale A and 38 on scale B to give 0.36 on scale C.

(b) Between 0.36 on scale C and 20 (altitude of obstruction to clerestory= 20 deg.) on scale D to give 0.30 on scale E.

(vi) Hence the values obtained from Nomogram I are:—

Average indirect component due to main window—0.77 per cent.

" " " " " clerestory—0.30 per cent.

The corresponding values obtained from the worked example of Appendix I are 0.81 per cent. and 0.33 per cent. respectively.

The discrepancies between the two sets of values can be attributed to the fact that the classroom in question had a floor of reflection factor 20 per cent., whereas the Nomogram relates to a room having a floor of reflection factor 15 per cent. These discrepancies are not of practical importance.

(vii) In practice, the calculation of the average reflection factor of the interior by the method suggested in Appendix 1 may be tedious, and an approximation to this reflection factor can be obtained from the table of Nomogram I simply from a knowledge of the wall reflection factor and the ratio of wall : total surface area. This assumes that the ceiling and floor reflection factors are 70 per cent. and 15 per cent. respectively.

In the present example the ratio of wall : total surface area $= \frac{1280}{3200} = 0.4$

The reflection factor of the walls = 30 per cent.

Hence from the table, the average reflection factor of the interior is 37 per cent.

(viii) If operations (iii), (iv) and (v) are repeated using a setting of 37 instead of 38 on scale B then the following values are given:—

Main Window

(a) 0.0525 on scale A	37 on scale B	0.79 on scale C
(b) 0.79 on scale C	10 on scale D	0.72 on scale E

Clerestory

(a) 0.0225 on scale A	37 on scale B	0.34 on scale C
(b) 0.34 on scale C	20 on scale D	0.28 on scale E

(ix) Hence the values obtained from the Nomogram are:—

Average indirect component due to main window — 0.72 per cent.

" " " " " clerestory — 0.28 per cent.

The discrepancies between these values and those obtained in (vi) are due to the difference between the approximate average reflection factor of the interior (37 per cent.) and the true value (38 per cent.).

(x) With the aid of Nomogram II values similar to those given above can be obtained corresponding to the *minimum* values of the indirect component. These

Table 7

Comparison between Values of Indirect Component of Daylight Factor obtained with Proposed Formula and with Nomogram II.

Method of Calculation	Average reflection factor of interior	Indirect component (per cent.)	
		Main window	Clerestory
Proposed formula (Appendix I)	True value (38 per cent.)	0.53	0.21
Nomogram II	True value (38 per cent.)	0.49	0.19
Nomogram II	Approximate value (37 per cent.)	0.45	0.17

values occur at positions in the room farthest from the window to which they relate. The values are given in Table 7.

The discrepancies which occur between the values calculated by the proposed formula and those obtained from Nomogram II are again attributable to the reasons given earlier in respect of the values given by Nomogram I.

Results obtained from the Nomograms will agree with those obtained by calculation when the conditions are similar to those assumed in the construction of the Nomograms. However, if the conditions are very different, e.g., dark ceilings, light floors, high ceilings or extreme room proportions, the Nomograms will produce an error dependent in magnitude on the extent of the departure from the basic conditions.

The scales on the Nomograms are restricted in their range to enable greatest accuracy to be obtained for most practical conditions. It is possible however that rooms will have to be considered which lie outside the normal range of the Nomograms. The ranges of the scales A, C and E (which are logarithmic) can be changed by any convenient factor (usually some power of 10), e.g., scale A on Nomogram I can be made to read from .001 to .02 if scales C and E are also changed by the *same* factor, i.e., scale C will read from .002 to 1 and scale E from .01 to .2. *Scales B and D should on no account be changed as they are non-logarithmic empirical scales.* Thus to change the range of the Nomogram, scales A, C and E should *all* be changed by the *same* factor but scales B and D should be unaltered.

Additions to the List of Members

The following applicants have been duly elected by the Council to membership in the Society and their names have been added to the list of members:—

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Thorn Electrical Industries (S.A.), (Pty), Ltd..... *Representative*: D. N. Lee.
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Two Supplementary Studies on Glare

By R. G. HOPKINSON, Ph.D., M.I.E.E., *(Fellow)*,
and P. PETHERBRIDGE, B.Sc., *(Member)*

Summary

An investigation has been made to see if assessments of glare discomfort in model-scale lighting installations are significantly different from assessments made in full-scale installations.

A further study has been made to see how far the general population differs in its assessments of glare discomfort from observers experienced in subjective judgments.

The results show that the experimental data and empirical formulae derived from model-scale studies on glare can be applied with confidence to the design of full-scale lighting installations, and that the glare conditions derived directly from these formulae will satisfy about 85 per cent. of the general population.

(1) Introduction

The use of model-scale lighting installations in the study of glare phenomena enables the relevant physical conditions to be varied independently over a wide range, and so permits the conditions likely to be met with in practice to be bracketed. This procedure gives greater confidence in the validity of the empirical relations obtained from the studies.

The employment of a limited number of experienced subjects who are readily available for making observations permits a large amount of data to be accumulated under identical conditions, so that the variance of the observations can be determined by accepted statistical procedures.

The empirical relations obtained from such studies must, if they are to be applied to practical lighting problems, be verified under full-scale conditions and for the general population. This verification can be obtained by field studies, as was done under street lighting conditions[1], or it can be obtained by suitable laboratory studies. Both methods have been employed here.

(2) Model versus Full-scale Experiments

(2.1) Experimental Studies

This paper only summarises the work undertaken for this investigation, and so the full experimental layout will not be described.

(2.1.1) *Full-scale Installations*

Two installations were used in the experiments. One consisted of two opal globes, and the other of a bare fluorescent lamp. Each installation was set up in turn in a room about 20 ft. × 10 ft., decorated as an office but free from distracting details. The observer sat about 14 ft. from the light sources, which were about 3 ft. 6 in. above his eye level. The luminances of the sources could be varied from a very low level to maxima of 1,900 ft.-lamberts and 4,700 ft.-lamberts for the fluorescent and filament sources respectively. The general background luminance in the office was provided partly by the illumination from the light source itself, but chiefly from concealed "topping-up" sources. The observer was asked to look at, but not to fixate on, a mark located about 10 deg. below the direction of the light sources.

(2.1.2) *Model Scale Installations*

Two installations, identical as far as possible with the full-scale display, were simulated in the model apparatus[2].

The authors are with the Department of Scientific and Industrial Research at the Building Research Station, Watford, Herts. The manuscript of this paper was received on January 18, 1954.

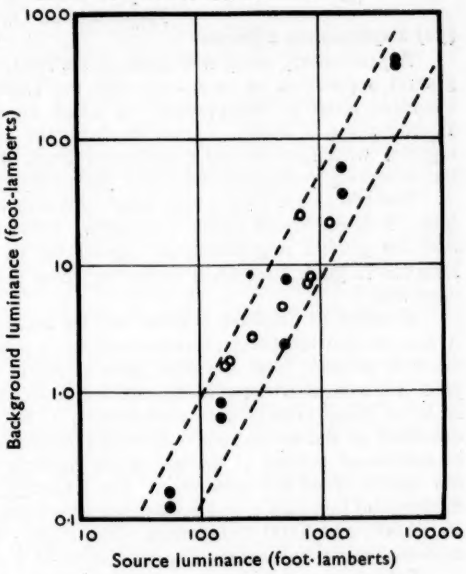

Fig. 1. Comparison between assessments of "just acceptable" glare made by an observer in model and full-scale lighting installations comprising two opal globes.

●●●● *Model-scale assessments.*
○○○○ *Full-scale assessments.*
– – – – *95 per cent. confidence limits of model-scale assessments.*

(2.2) Procedure and Results

The experimental procedure was not difficult for the subject; the experimenter, on the other hand, had to operate numerous controls. The observer was asked to report when each of four criteria of glare, previously described to him, were obtained. These criteria were "Just Imperceptible" glare (Criterion D, see ref. (2)), "Just Acceptable" glare (Criterion C), "Just Uncomfortable" glare (Criterion B), and "Just Intolerable" glare (Criterion A). Combinations of source luminance and background luminance (the latter varied by "topping-up") gave each of the glare criteria under different conditions.

On the model scale the procedure was the same as for the earlier investigation(2). The order in which the installations were presented was varied from time to time.

The results are probably best presented in the form shown in Fig. 1. This shows the results obtained by one observer for one criterion together with the 95 per cent. confidence limits which apply to this observer under model-scale conditions. Each observer had undertaken "control" observations over a long period, sometimes for months or years, and it is from these extensive "control experiments" that the confidence limits were taken. The individual assessments made during the present study are shown on the same diagram. Similar observations were obtained with the other criteria of discomfort, and by the other observers. An examination of the diagram shows that all the assessments made under the full-scale conditions fall within these confidence limits. This was true also for the other data. Bearing in mind the various reasons which would contribute to random errors in the assessments, there is no evidence from the observations to suggest that assessments made on a full scale will differ significantly from those made under laboratory conditions.

The observations from the "fluorescent" installation show the same result.

(3) Relative Sensitivity to Glare of General Population and of Experienced Observers

(3.1) Experimental Procedure

A preliminary study was made of the relative sensitivity to glare discomfort of the general population as compared with the experienced observers who had made the extensive series of observations on which an empirical glare formula[2] was based. Twenty subjects chosen at random from the staff of the Building Research Station, together with four of the experienced team, made assessments in the model under the observing procedure described previously[2].

The results revealed a very large spread in the observations of the general population. This confirmed earlier studies[1]. There was, however, also a clear indication that the general population, as represented by this team of 20 observers, was less sensitive to glare discomfort under the given conditions than the team of experienced observers.

In order to establish a more reliable statistical basis for this relative sensitivity, it was decided to obtain measurements on a much larger sample. Fifty subjects were taken at random from the staff (both scientific and non-scientific). Each of the subjects was instructed how to operate the model apparatus, and the significance of the scale of glare criteria was explained[2]. The observing procedure was exactly as described in the earlier paper although rather more help was necessary to guide the inexperienced subject in the use of the multiple-criterion method of judgment and in the operation of the apparatus. The variable under the subject's control was the background luminance, and judgments were made at three levels of source luminance—300, 1,000, and 3,000 ft.-lamberts. The display used was that shown in Fig. 3 of the earlier paper[2], consisting of a simulation of a school classroom lit by opal globes.

The observer visited the apparatus only once, making 12 readings in all (four criteria at each of three levels of source brightness). These readings were compared with 50 sets of readings which had been obtained by the experienced team over a period of four months on the same apparatus, concurrently with the observations on which the empirical glare formula [2] was based.

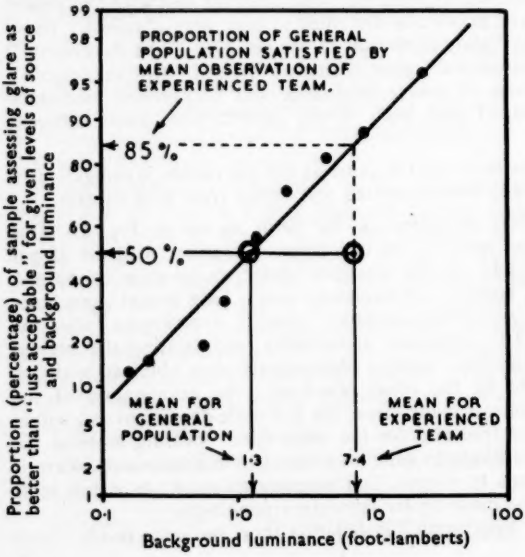

Fig. 2. Relation between mean observation of the experienced team and observations of the general population on glare discomfort.
Criterion "C"—just acceptable. Source luminance—1,000 foot-lamberts.

(3.2) Results

The results of this study confirmed that the experienced team was more sensitive to glare discomfort than the general population as represented either by these 50 observers or by the previous 20 observers.

Fig. 2 illustrates a typical result for sources having a luminance of 1,000 ft.-lamberts, and examines the conditions to give a degree of discomfort described as "just acceptable." The probability of the general population experiencing that particular degree of glare is shown related to the value of the background luminance. The average of the general population is prepared to accept a background luminance of 1.3 ft.-lamberts. On the other hand, the average of the experienced team requires 7.4 ft.-lamberts, at which level 85 per cent. of the general population would be satisfied. This means that in general a condition of glare discomfort which is accepted by half the experienced subjects would be accepted by five out of six of the general population. Similar data exist for other levels of glare, and for each of the three source luminances examined.

Certain factors must, however, be taken into account in assessing the value of results obtained in a psycho-physical experiment with unskilled subjects. If the experiment demands a high degree of judgment ability, as does the glare experiment, it will follow that a degree of variance will be introduced due to any lack of this judgment. This variance can arise in at least three ways.

First, the task of making a judgment often taxes the intelligence too much, and although the subjects try to do what is asked of them they cannot exercise the necessary judgment. To such people, for example, the only degree of glare that they can recognise is that received from the headlights of an oncoming car, or from low angle sun shining directly in their eyes. Clinicians find the same inability to recognise graduations in the severity of pain.

Another category of unsatisfactory observer is the subject who feels that his judgment must be either "right" or "wrong" and who strives to be "right," but who is unable to decide how to make his judgment. (Such a subject can, in fact, be given confidence and may become a useful observer, but he is then "experienced" and of no value for the present study.)

Finally there is the subject who is unco-operative and who makes no effort to give a sound judgment.

These three categories of unsatisfactory subject are always present in a random

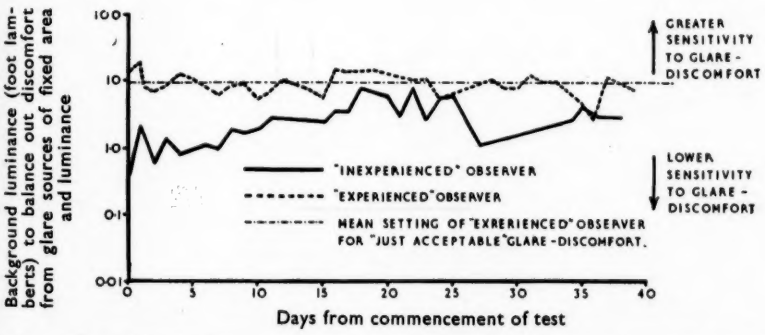

Fig. 3. Glare-discomfort assessments of an "inexperienced" and an "experienced" observer under identical conditions over periods of about 40 days for "just acceptable" criterion, showing increasing sensitivity of "inexperienced" observer to glare-discomfort over the period.

sample. They introduce a variance which is not in any way a function of the visual mechanism which controls glare.

Some knowledge of this variance has been obtained from other studies (Ref. 3, Fig. 2). It can be detected and eliminated by suitable experimental design (e.g., by repeated presentation, unknown to the observer, of the same conditions). This was not possible in the present investigation, and so the results include this variance due to difficulty in judgment. The existence of this variance is, of course, one of the arguments for conducting subjective studies with panels of skilled and intelligent subjects.

(3.3) Increase of Sensitivity to Glare with Increasing Experience

It is relevant to recall that experiments have shown that an inexperienced observer becomes progressively more sensitive to glare as his experience increases, until he acquires a sensitivity which remains constant and a maximum[4] [5] (See Fig. 3).

(4) Conclusion

The evidence of this investigation shows that the empirical formulae derived from model studies can be applied directly to practical lighting calculations, and that if this is done the majority of the general population will have their demands met.

No systematic field studies on this problem have been undertaken, but in the course of many inspections of lighting installations the opportunity has been taken to assess the degree of glare discomfort prevailing. In spite of the fact that many of these installations have been of an unusual character, e.g., concert halls, debating chambers, offices lighted with special diffusing glass windows, the assessments made in the field have none the less been found to agree with those predicted from the empirical formulae within the known variances.

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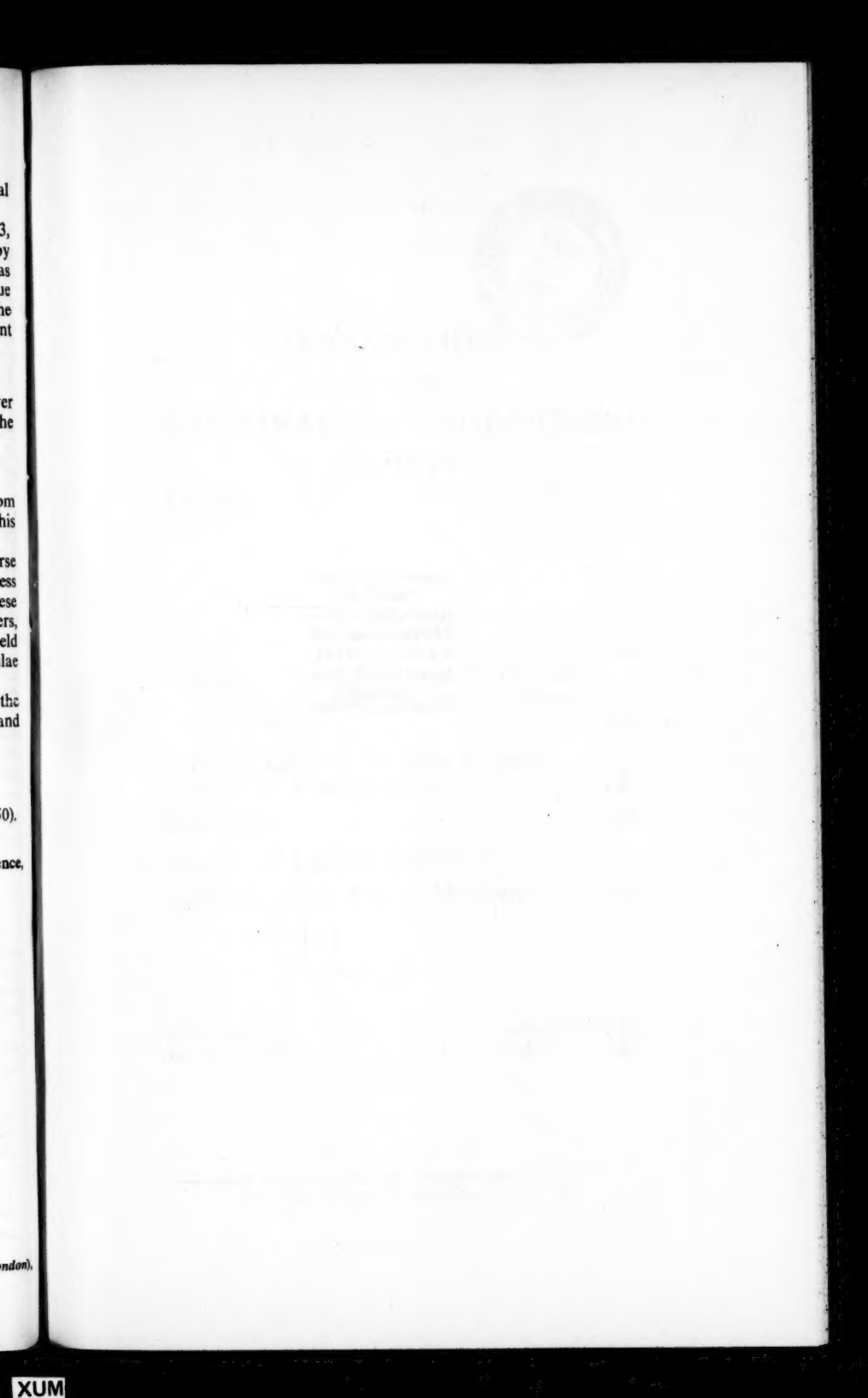

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